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Corrosion of Stainless-Steel Tubing in a Spacecraft Launch Environment

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ABSTRACT

This is a report of exposure of various metal tubing to oceanfront launch environment. The objective is to examine various types of corrosion-resistant tubing for Space Shuttle launch sites. The metals were stainless steels (austenitic, low-carbon, Mo-alloy, superaustenitic, duplex, and superferritic), Ni-Cr-Mo alloy, Ni-Mo-Cr-Fe-W alloy, and austenitic Ni-base superalloy.

Keywords: tubing, stainless steel, nickel, corrosion, spacecraft launch environment

INTRODUCTION

The objective of this project is to test and examine various types of corrosion-resistant tubing for use at Space Shuttle launch sites. The existing 304-stainless-steel tubing at Launch Complex 39 (LC-39) launch pads is susceptible to pitting corrosion. This pitting corrosion can cause cracking and rupture of both high-pressure gas and fluid systems. Failures of these systems can affect the safety of Shuttle launches as well as pose life-threatening conditions to personnel in the immediate vicinity. The use of a new tubing alloy for launch pad applications would greatly reduce the probability of failure, improve safety, lessen maintenance costs, and reduce downtime losses.

Procurement of Tubing Test Articles

Under NASA direction, 11 tube materials were selected for evaluation. All tubing materials specified were seam welded rather than seamless extruded and were delivered as line annealed. Table 1 lists the trade name, vendor, material class, and manufacturer of the materials used in testing. Other manufacturers were contacted for pricing and availability of product, but vendors listed in Table 1 best met the project's budget and time constraints. Table 2 lists trade name, ASTM standard specification, (UNS) number, percent chemical composition, tensile strength, and yield strength of each material.

Fabrication of Tubing Test Articles

Each tubing test article was prepared from three sections, an upper section, lower section, and a center section (Figure 1). The upper and lower sections each have a 90° bend, bent per KSC-SPEC-Z-0008C (Specification for Fabrication and Installation of Flared Tube). The center section is a 12-inch length of straight tube that has been cut and orbital-fuse welded back together. Welding was performed on an automated orbital welder per NASA-SPEC 5004 (Welding of Aerospace Ground Support Equipment and Related Non-Conventional Facilities). Only visual inspections of the welds were performed. The ends of each piece were flared adhering only to diameter dimensions listed in SPEC GP425F – KC154 (Fluid Fitting Engineering Standards). Table 3 lists the KSC-SPEC-Z-0007E (Specification for Tubing, Steel, Corrosion Resistant, Types 304 and 316, Seamless, Annealed) wall thickness variations and discontinuities for each alloy versus the ASTM standards.

Each piece of tubing was pressure proof tested per KSC-SPEC-Z-0008C and blown dry with GN_2 before being assembled. 304-stainless-steel KC fittings were then used to assemble the three sections of tubing together in an S-shaped configuration as shown in Figure 1. A pressure gauge was attached to the top end of the tubing, and a ball valve was attached to the lower end for tube pressurization/isolation. Once assembled, the tubing test articles were placed on fabricated stands, pressurized to approximately 2000 psi and checked as an assembly for leaks. The stands were then transported to the KSC Beach Corrosion Test Site during the week of March 6-9, 2000 for test and evaluation.

A total of 98 tubes were mounted on four stands. Two of the four stands were built with a protective roof (cover). The covers were put in place to reduce the sun and rain exposure of the test articles. Table 4 lists the tubing material, tubing OD, placement on the rack, rack covered (yes or no), acid wash (yes or no), and the number of tubes per rack. A table of workability problems that were encountered during fabrication of the tubing test articles can be found in the Appendix.

It should be noted that one tubing test article was fabricated from Material 254 SMO that was furnace annealed rather than line annealed. This tubing test article has been hung on rack # 2 (covered and acid rinsed). The workability for this sample was found to be superior to line-annealed tubing and was said to be comparable to the workability of the standard 304 stainless-steel used presently on center. Figure 2 shows an overview of the four racks located at the beach corrosion facility.

Atmospheric Exposure at Kennedy Space Center Beach Corrosion Facility

The test matrix consists of four separate conditions that could be experienced at the launch facilities. The conditions are as follows: normal seacoast unsheltered, normal seacoast sheltered, acid environment unsheltered, and acid environment sheltered. A 10 perent (v/v) solution of concentrated hydrochloric acid (HCl) and 28.5 grams of alumina powder per 500 ml of solution was mixed into an acid slurry to simulate solid rocket booster (SRB) deposition. Two of the four racks are sprayed every two weeks with the acid slurry to accelerate the corrosion effect. One rack is covered and the other is not. Figures 3 through 6 show racks 1 through 4, respectively, after 20 weeks of atmospheric exposure and 4 applications (8 weeks) of the acid slurry.

Evaluation of Corrosion Resistance

Preliminary evaluation of the tubing test articles shows that all of the nickel-based alloys (primary constituent nickel), C-2000, C-276, and 625 along with iron-based alloys 254 SMO and 2507, shows little signs of corrosion. The 304L, 316L, and 317L alloys show the greatest signs of corrosion. AL-6XN shows distributed corrosion over the entire surface of the tube. Earlier testing showed that this same material had better corrosion resistance under similar test conditions. It has been suggested that the tubing surface was not properly conditioned, causing the difference in performance. The remaining alloys, AL29-4C and 2205, show moderate oxidation. Table 5 ranks the alloys from best to worst. Both acid-washed racks show much more corrosion than the racks that have only been exposed to atmospheric conditions. Figures 7 through 15 show the different alloys mounted on rack 1 in the order that they are placed on the rack from left to right. Rack 1 has been acid washed and is not covered. This rack seems to show the highest signs of corrosion to date. Both acid-washed racks show much more corrosion than the racks that have only been exposed to atmospheric conditions.

Besides the apparent high nickel content in the three nickel-based alloys, the top five performers have higher levels of molybdenum (6.1 to 16.0 percent) with the exception of 2507, which only has 4 percent. The AL6-XN with a molybdenum level of 6.0 to 7.0 percent showed a much higher level of corrosion than the top five. All the 300-series stainless steels with molybdenum levels of less than 4 percent (304L with 0 percent) showed the highest level of corrosion.

Performance and Cost Benefits for Shuttle Launch Complex 39

At this time, more data needs to be collected and the alloy materials need to have more exposure time before conclusive results can be obtained. As mentioned above, the 300-series stainless steels have performed the worst. It is noted that these 300-series stainless steels all have a low carbon content reducing the effects of intergranular corrosion but lack sufficient levels of molybdenum to be highly effective against pitting corrosion. Workability of the majority of tubing was not favorable, but getting furnace-annealed tubing in the future should reduce these concerns. Currently, no new tubing is scheduled for purchase, and the differences in annealing processes should not affect the ongoing corrosion testing. It is recommended that the AL6-XN tubing be replaced with pickled AL6-XN to address concerns that the original AL6-XN was not properly treated for testing. Some tubing alloys demonstrate improved corrosion resistance if pickled during the manufacturing process.

Costs of the different tubing materials fluctuate somewhat with changes in market prices of the different alloying elements. Nickel is one of the larger cost factors due to the large percentages used in these alloys. Table 6 lists the manufacturer/supplier, material, tube OD, wall thickness, cost per foot, and lot size as an example of some current manufacturers' tubing prices. All the tubing costs quoted are for ASTM standard, seam-welded, line-annealed tubing with the exception of the first two line items. These line items represent current Federal stock-supplied 304 seamless stainless-steel tubing and their current costs. It should also be noted that the tubing purchased from International Tubular Product did not come factory pickled. Prices will vary among suppliers and quantities purchased, as well as any treatments or stricter tolerances desired.

CONCLUSIONS

The strongest effect on corrosion in this study is the metal type. Evaluation of the tubing test articles showed that all of the nickel-based alloys (C-2000, C-276, and 625, along with iron-based alloys 254 SMO and 2507) showed little signs of corrosion. The 304L, 316L, and 317L alloys showed the greatest signs of corrosion. AL-6XN showed distributed corrosion over the entire surface of the tube, but earlier testing showed that this same material had better corrosion resistance under similar test conditions. The AL-6XN tubing surface was not properly conditioned (pickled), likely causing the difference in performance. AL29-4C and 2205 showed moderate oxidation. Both acid-washed racks show much more corrosion than the racks that were only exposed to atmospheric conditions. Workability of the majority of tubing was not favorable, but furnace annealing should reduce this problem.

APPENDIX

Material	Cutting, Squaring, Deburring	Flaring	Bending	Hydrostat	Notes
254 SMO	Material seems to harden while cutting; extremely hard to trim after cutting to length; wore trimming blades very fast; burned and chipped even with plenty of lubricant; blades bounced off seams.	Flares have flat spots where the seam is located.	Seam must be on inner radius otherwise splitting occurs.	Due to flat spots on flares, all joints had to be overtorqued.	Weld splatter from seams had to be removed from inside the tube prior to welding; inconsistent seams protruding into the ID of the tube caused welding problems. Had shop face tubing before trimming and flaring, resulting in better performance; poor welded seam quality.
304L	Hard to cut if seam is in the upper position; some seams were too high, which damaged trimming and cutting blades.	Some seams cracked during flaring, some went flat.	Tubing bent OK but there seemed to be some extra stretching. This could be due to the undersized OD and its out-of-roundness.	Most connections had to be overtorqued to seal.	Tubing seemed to be very out-of-round; poor welded seam quality.
C-2000	It was extremely hard; used a lot of Portaband saw blades and trimmer blades. The seams were inconsistent.	Flares formed well.	No Major Problems.	No problems. Fittings required no extra torque.	Hard to weld because it was hard to dial in the machine; fit has to be almost perfect for good results; poor welded seam quality.
317L	No problems; very easy to work with.	No problems.	Seam had to be on the inner radius or the tube would flatten.	No problems.	No problems.
AL6XN	No Comments given.	Seams cracked during flaring.	No Comments given.	No comments given.	Worst material to work with; poor welded seam quality.
316L	No Comments given.	No Comments given.	Seam had to be on the inner radius or the tube would flatten.	No comments given.	Seams were fair but material welded well.
2205	No problems.	No problems.	Seam had to be on the inner radius or the tube would flatten.	No problems.	No problems.
C276	It was extremely hard; used a lot of Portaband saw blades and trimmer blades.	Flaring was quite difficult; some flares split at the seams.	Bending was difficult; the seam had to be on the inner radius or the tube would flatten.	Difficult; all joints had to be overtorqued.	Welded seams were very inconsistent.
625	It was extremely hard; used a lot of Portaband saw blades and trimmer blades.	No problem once it got trimmed; flares looked really good.	Went well but was best to have seam on inner radius.	Some of the welded seams on the flares produced problems and had to be overtorqued.	No comments given.
AL29-4C	No problems; very easy to work with.	No problems.	No problems.	No problems.	No comments given.
2507	No problem; easy to work with.	No problems; flared nicely; no problems with welded seams in flare area.	Bent nicely, but it was best to have the welded seam on the inner radius.	No Problems.	No comments given.

Table 1
Test Materials

Material	Class
254 SMO	Austenitic Stainless Steel
304L	Low-Carbon Austenitic Stainless Steel
C-2000	Nickel-Chromium-Molybdenum Alloy
317L	Molybdenum-Containing Austenitic Stainless Steel
AL-6XN	Superaustenitic Stainless Steel
316L	Molybdenum-Bearing Austenitic Stainless Steel
2205	Ferritic-Austenitic (Duplex) Stainless Steel
C276	Nickel-Molybdenum-Chromium-Iron-Tungsten Alloy
625	Austenitic Nickel-Based Superalloy
AL29-4C	Superferritic Stainless Steel
2507	Ferritic-Austenitic (Duplex) Stainless Steel

Note: All alloys are listed in the order that they are placed on the test racks.

Table 2
Percent Composition and Strength of Materials

Material	ASTM	UNS #	Fe	Ni	Cr	Mo	Mn	C	N	Si	P	S	Cu	Al	Ti	V	Co	W	Ti-Nb	Nb-Ta	Ten-sile Ksi /(MPa)	Yield Ksi /(MPa)
254 SMO	A269	S31254	54.7-55.2	18.0	20.0	6.1		0.010	0.20				0.50-1.00								94 (650)	46 (320)
304L	A269	S30403	65.1-71.1	8.0-12.0	18.0-20.0		2.00	0.030		0.75	0.045	0.03									75 (515)	30 (205)
C-2000	B626	N06200		59.30	23.00	16.00		< 0.01		< 0.08			1.60								109 (752)	52 (358)
317L	A213	S31703	58.1-65.1	11.0-15.0	18.0-20.0	3.00-4.00	2.00	< 0.03		0.75	0.045	0.03									85 (586)	40 (276)
AL-6XN	B676	N08367	43.7-48.7	23.5-25.5	20.0-22.0	6.00-7.00	0.40	0.020	0.18-0.25	0.40	0.025	0.002	< 0.75								110 (760)	55 (380)
316L	A249	S31603	62.0-69.0	10.0-14.0	16.0-18.0	2.00-3.00	2.00	0.030	0.10	0.75	0.045	0.030									70 (485)	25 (170)
2205	A789	S31803	69.3	5.50	22.00	3.00		0.020	0.17												94 (650)	68 (470)
C-276	B626	N10276	6.00	58.30	15.50	16.00	0.15	0.004		0.03	0.005	0.002				0.15	0.1	3.5			100 (690)	41 (283)
625	B704	N06625	4.00	60.30	22.00	9.00	0.30	0.050		0.25	0.010	0.003		0.3	0.3					3.5	136 (940)	63 (430)
AL29-4C	A268	S44735	65.20	0.30	29.00	4.00	0.50	0.020	0.020	0.35	< 0.01	0.030							0.6		75 (515)	60 (415)
2507	A789	S32750	63.70	7.00	25.0	4.00		0.020	0.27												107 (740)	78 (540)

Note: All alloys are listed in the order that they are placed on the test racks.

Table 3
Wall Thickness Variations and Discontinuities

Material Trade Name	Tubing OD (in)	wall (in)	KSC-SPC-Z-0007E OD variations +	-	Discontinuity wall thk min (in)	ASTM Spec	OD variations + (in)	- (in)	% var wall thk +	-
254 SMO	1.0	0.065	0.005	0.000	0.004	A269	0.005	0.005	10	10
304L	1.0	0.065	0.005	0.000	0.004	A269	0.005	0.005	10	10
C-2000	0.75	0.065	0.005	0.000	0.004	B626	0.004	0.005	12.5	12.5
C-2000	1.0	0.065	0.005	0.000	0.004	B626	0.006	0.006	12.5	12.5
317L	0.75	0.065	0.005	0.000	0.004	A450	0.004	0.004	18	0
AL-6XN	0.75	0.065	0.005	0.000	0.004	B751	0.0075	0.0075	12.5	12.5
316L	0.75	0.065	0.005	0.000	0.004	A249	0.004*	0.004*	10	10
2205	1.0	0.065	0.005	0.000	0.004	A789	0.005	0.005	10	10
C276	0.75	0.065	0.005	0.000	0.004	B626	0.004	0.005	12.5	12.5
625	0.75	0.065	0.005	0.000	0.004	B751	0.0075	0.0075	12.5	12.5
AL29-4C	0.75	0.049	0.005	0.000	0.003	A268	0.005	0.005	10	10
2507	0.75	0.065	0.005	0.000	0.004	A789	0.005	0.005	10	10

* ASTM Standard A450

ASTM A450 gives the general requirements for carbon, ferritic alloy, and austenitic alloy steel tubes

ASTM B751 gives the general requirements for nickel and nickel alloy welded tube

Note: All alloys are listed in the order that they are placed on the test racks.
Abbreviations: *thk*: thickness; *var*: variation; *min*: minimum

Table 4
Rack Configuration

Rack	Cover	Acid Wash	254SMO 1"	304 L 1"	C2000 1"	C2000 3/4"	317 L 3/4"	AL-6XN 3/4"	316 L 3/4"	2205 1"	C276 3/4"	625 3/4"	AL29-4C 3/4"	2507 3/4"	Totals
1	no	yes	3	3	1	2	3	3	3	2	2	1	1	1	25
2	yes	yes	3	3	1	2	3	3	2	2	2	1	1	1	24
3	no	no	3	3	1	2	3	2	3	2	2	1	1	1	24
4	yes	no	3	3	1	2	3	2	4	2	2	1	1	1	25
		Totals	12	12	4	8	12	10	12	8	8	4	4	4	98

Note: All alloys are listed in the order that they are placed on the test racks.

Table 5
Corrosion Condition Ratings

Alloy	Base	Ranking
C-2000	Nickel	(Good) Shows little or no corrosion
C276	Nickel	(Good) Shows little or no corrosion
625	Nickel	(Good) Shows little or no corrosion
254 SMO	Iron	(Good) Shows little or no corrosion
2507	Iron	(Good) Shows little or no corrosion
AL29-4C	Iron	(Fair) Shows surface oxidation
2205	Iron	(Fair) Shows surface oxidation
AL-6XN	Iron	(Fair-Poor) Shows general corrosion over the entire surface of the tubing. Note: Earlier testing has shown that this alloy had greater corrosion resistance to similar conditions. (It has been speculated that the tubing used in the earlier test had been pickled.)
304L	Iron	(Poor) Shows general corrosion over the entire surface of the tubing.
316L	Iron	(Poor) Shows general corrosion over the entire surface of the tubing.
317L	Iron	(Poor) Shows general corrosion over the entire surface of the tubing.

Table 6
Cost Comparisons

Manufacturer/Supplier	Material	OD (in)	Wall thk.(in)	$/foot	Lot Size (ft)
Federal Stock-Supplied (seamless)	304	3/4	0.065	$9.48	SPC
Federal Stock-Supplied (seamless)	304	3/4	0.065	$2.52	BOC
Commercial	254 SMO	3/4	0.065	$3.54	1000
Commercial	304L	3/4	0.065	$1.10	1000
Commercial	2205	3/4	0.065	$1.75	1000
Commercial	2507	3/4	0.065	$3.41	1000
Commercial	C-2000	3/4	0.065	$14.96	1000
Commercial	317L	3/4	0.065	$2.68	1000
Commercial	AL-6XN	3/4	0.065	$3.70	10000
Commercial	316L	3/4	0.065	$1.10	10000
Commercial	C276	3/4	0.065	$6.60	10000
Commercial	625	3/4	0.065	$6.40	10000
Commercial	AL29-4C	3/4	0.049	$1.88	10000

Note: All tubing is standard off-the-shelf ASTM spec. seam-welded tube unless otherwise specified.
Both Federal Stock-supplied tubing have same stock number (4710-01-015-1268)